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# 3 Detection of Biologic Signals

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*Reed M. Gardner*

## Principles

Review of electrical elements

## How common transducers operate

Electrocardiogram electrode

Pressure transducers

Temperature transducers

Measurement of respiratory gas flow

Measurement of respiratory gas  
concentration

## The future of signal detectors

## PRINCIPLES

In recent years, the use of our five senses (sight, hearing, smell, taste, and touch) has been augmented with exciting new and powerful medical instruments. These devices must each have a "sensor," or signal detector, as the initial detection device. Signal detectors or sensors are also called transducers. Transducers are devices that convert energy from one form to another. With modern instrumentation technology, physiologic signals of various sorts such as blood pressure and temperature are usually converted to electrical signals. Conversion to an electrical signal is made because of the existence of such a wide variety of excellent electrical signal processing capabilities. These capabilities include amplifiers that can boost minute signals and the capability to convert the physiologic signal quickly to a "digital" form so that it can be processed and stored by a computer.

Fig. 3-1 is a block diagram of a typical medical instrumentation system. Information of various types is derived from the patient (*left*) and presented (*right*) for review by clinical staff.<sup>1</sup> A physical parameter measured by the system is called the *measurand*. For example, the measurand may be the patient's blood pressure or electrocardiogram (ECG). The *sensing element*, or transducer, usually converts one form of energy to another (for example, a blood pressure transducer). The ideal sensor is one that is minimally invasive and extracts the minimum amount of energy possible

from the patient. Frequently these sensing elements require electrical power (for example, the blood pressure transducer). Sensing elements cannot generally be connected directly to the display device. Thus, virtually all sensing elements are sent to a *signal processor*. The signal processor typically contains an amplifier, filter, and analog-to-digital conversion equipment. Details of signal processing are presented in Chapter 4.

Comprehensive coverage of signal detectors used in acute care monitoring is a difficult task. Texts have been written on the subject.<sup>1-5</sup> A recent medical device encyclopedia further illustrates the size of the task.<sup>2</sup> This encyclopedia is made up of four volumes with 2500 pages and over 250 articles! In addition, numerous articles have been and are continually being written on the subject. Indeed, more dramatic improvements in medical instrumentation have been seen in the last 25 years than in the previous centuries. The invention of semiconductor materials, which led to the transistor and integrated circuit, as well as all the related technologies have opened up wonderful opportunities for scientists to develop signal detectors that were heretofore unthinkable.

Many of the newer medical measurement instruments have much more capability to make accurate and continuous measurement of parameters than we as humans have ever had. For example, pulse oximeters can now quickly and accurately measure arterial oxygen saturation and heart rate

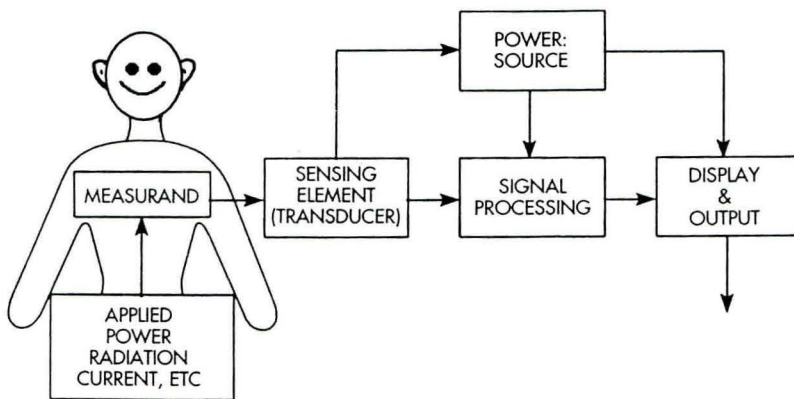
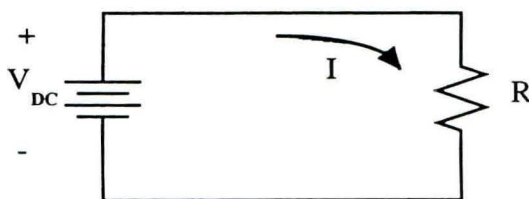


Fig. 3-1. Block diagram of medical instrumentation.

noninvasively (without breaking the skin). In the past clinicians had to make observations about saturation by noting that the patient was “blue,” thus using an inaccurate method.<sup>6</sup> As a result of new technology, a constant source of patient physiologic information is available that in the past was either impossible or very expensive to obtain.

Virtually every medical instrument has at its core a sensing element or transducer. The accuracy, reliability, cost, and reusability of the sensor relates to the value of the signal detected. No manner of signal processing can make up for an inadequate sensor. The ideal sensor should interface with the patient in such a way that the energy extraction from the patient is minimal and at the same time minimally invasive. For example, a pressure transducer has a diaphragm as its primary sensing element. The motion of the diaphragm is then detected by a conversion element, usually an electrical strain gauge. Often the sensitivity of the transducer can be adjusted. For example, a pressure transducer may be required to measure both venous (−10 to +30 mmHg) and arterial pressure (20 to 300 mmHg).

By their nature most transducers, and as a consequence the electrical signals they generate, are “analog” devices. An analog signal is one that is continuous and able to take on any value within the dynamic range of the device. For example, a blood pressure transducer may be capable of measuring pressure over the range of −20 to +300 mmHg. Since it is an analog device it can measure pressures continuously and could therefore measure a pressure of 123.56 mmHg. In most cases there is not a need for such resolution, but with an analog device it is possible. On the other hand, digital signals take on only a finite number of different discrete values. For example, think of the digital scales that you might have in your bathroom at home. Typically these scales will weigh and display values only to the nearest pound. Try as you might, you as the user will be unable to

Fig. 3-2. Ohm's law and battery with resistor. *V*, Voltage; *DC*, direct current; *I*, current in amperes; *R*, resistance in ohms.

change this resolution limit. The advantages to digital signal acquisition and processing are the possibility for greater accuracy, repeatability, reliability, and immunity from noise or unwanted signals. Consequently, most transducers produce analog electrical signals that are quickly converted to a digital form for processing and display. (See the section in Chapter 4 on signal conditioning for further discussion.)

### Review of electrical elements

Ohm's law is a basic law of physics that relates voltage and current to resistance. Fig. 3-2 is a diagram of a simplified electrical circuit with a battery and a resistive element. If the battery provides a voltage, *V*, and the resistance in ohms is *R*, then the current, *I*, in amperes flowing through the resistor is *I*. Ohm's law indicates that  $V = IR$ .

For electrical circuits there are two types of current: DC or direct current is the type of power or current that is derived from the battery in an automobile or flashlight. The other type of power or current is referred to as AC or alternating current. AC power or current is available through the power outlets in our homes to run appliances, electrical lights, and so forth. In the United States, the household current operates at 60 Hz (hertz or cycles per second) and has a sinusoidal characteristic (Fig. 3-3).

Fig. 3-4 shows circuits with DC and AC excita-



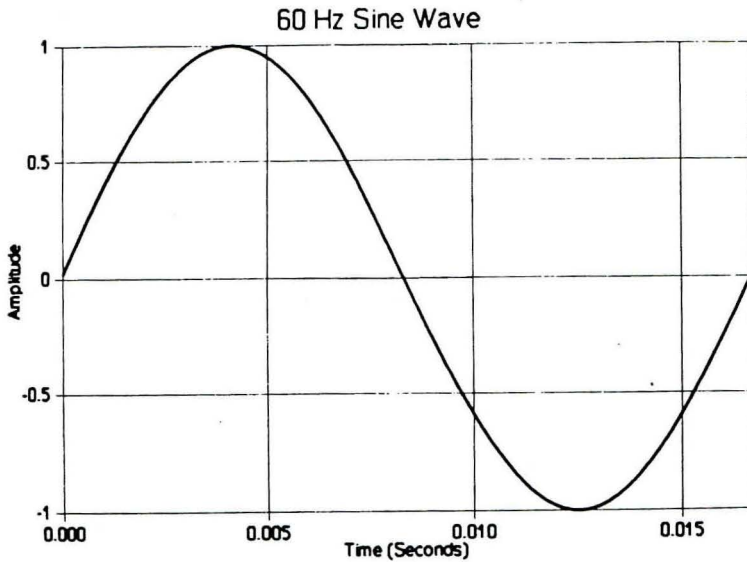


Fig. 3-3. Sinusoidal waveform (LOTUS plots).

tion. Note that with AC excitation two additional electrical circuit sensing elements are possible. These are capacitors ( $C$ ) and inductors ( $L$ ). There are transducers that change their resistance, capacitance, and inductance when a physiologic signal is applied to them. While Ohm's law applies to resistors, the equivalent for AC impedance is reactance for capacitors and inductors and resistors (Fig. 3-4 supplies equations).

## HOW COMMON TRANSDUCERS OPERATE

### Electrocardiogram electrode

Electrocardiogram (ECG) monitoring has become a standard practice for the measurement of heart rate, rhythm, and myocardial ischemia; therefore, the signal quality must be reliable. Although the ECG electrode is perhaps the simplest medical transducer, it is also one of the most complex and misunderstood.<sup>1,7</sup> The electrical activity of the

heart can be detected on the body surface, but is a very small signal (about 1 mV). To faithfully reproduce the ECG and display the signal it is necessary to eliminate undesired signals known as noise or artifact. Other signals that frequently interfere with the ECG signal are 60 Hz (50 Hz in Europe) from power lines and electrosurgery cauterizing equipment. Fig. 3-5 shows a schematic diagram of an ECG electrode attached to the skin.

What seems simple as we "slap on" a disposable ECG electrode is not so simple. The stratum granulosum has a resistance of about 50 kOhm/cm<sup>2</sup>. Proper skin preparation can reduce electrode resistance from as much as 200 kOhm to as little as 10 kOhm. In addition there is a skin potential of about 30 mV across the stratum granulosum. Stretching the skin can cause a motion artifact of about 5 mV. However, if the skin is properly prepared by cleaning it with alcohol and slightly abrading it before application of the electrode, then artifact problem-

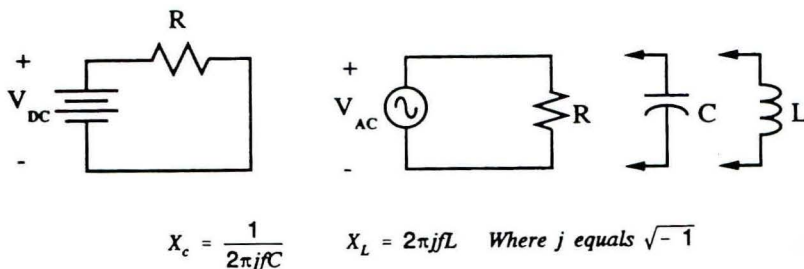
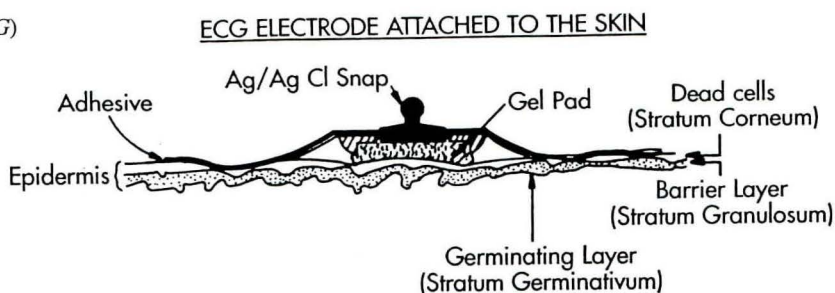


Fig. 3-4. R, C, L circuits with impedance.  $V$ , Voltage;  $R$ , resistance in ohms;  $C$ , capacitance in farads;  $L$ , inductance in Henries;  $f$ , frequency in Hertz (cycles per second);  $X_C$ , capacitance reactance;  $X_L$ , inductive reactance.

Fig. 3-5. Electrocardiogram (EEG) electrode diagram.



atic with ECG electrodes can be minimized.<sup>7</sup> After application of ECG electrodes, 15 to 30 minutes are required for the electrode gel to penetrate and form a stable electrode interface.

### Pressure transducers

The pressure transducer is used to measure arterial, pulmonary artery, or venous pressure.<sup>1,8-11</sup> Pressure transducers have elements in their configuration that change their resistance, capacitance, or inductance when pressure is applied. However, today, most pressure transducers used in clinical settings are based on resistive change and are called strain gauges.

The principle of electrical resistance strain-gauge transducers is not new; it was discovered in 1856 by Lord Kelvin. He noted that the resistances of metal wires increased with increased stretch or strain on them. He also noted that different materials produced different resistive changes with the same amount of stretch. Fig. 3-6 is a schematic example of a strain-gauge transducer. The Wheatstone bridge (Fig. 3-7) is the most common configuration used for resistive strain gauges. Typically, two of the resistors in the four-element active bridge configuration increase in resistance while two decrease in resistance as pressure is applied. Since every resistor changes its resistance slightly with temperature and other factors, by having the resistors matched there is little change in "zero," or sensitivity of the gauge with temperature.

Twenty years ago pressure transducers were handmade and were about the size of a popsicle. They cost about \$500 each. Today pressure transducers are typically about the diameter of an aspirin tablet with a thickness of only 0.4 mm! These transducers are mounted in plastic housings, and calibrated. Each costs less than \$20 and, therefore, is disposable. Catheter-tipped transducers that are of submillimeter size are now being made. Virtually all pressure transducers used today in clinical settings are made from silicon (glass) semiconductor materials. The same technology that is used to manufacture transistors and integrated circuits

commonly used in stereo and computer equipment is now being used to make pressure transducers.

Pressure transducers used in clinical medicine today are based on use of a diaphragm that deforms when pressure is applied. Typical pressure transducers have four tiny resistors electrically diffused onto their surface. To make the diaphragm thinner and thus more sensitive, a small hole is photographically etched into the underside to make a thin diaphragm. Volume displacement of typical pressure transducers is on the order of 0.1 mm<sup>3</sup>/100 mmHg applied. For a typical pressure transducer, the displacement is about 0.0001 mm<sup>3</sup> for each mmHg applied. As a frame of reference, the diameter of a typical human hair is about 0.05 mm. Thus the diaphragm movement is only about two thousandths of the diameter of a human hair!

Medical blood pressure transducers have been standardized by the American National Standards Institute (ANSI).<sup>8</sup> These transducers have sensitivities of 5 microvolts ( $\mu$ V) per volt of excitation per mmHg applied pressure. Typically about 5 V DC is applied to pressure transducers. Consequently, a signal level of 25  $\mu$ V is derived for each mmHg applied—a small signal indeed.

Fig. 3-8 shows a pressure transducer that measures the movement of the diaphragm by using a moving magnetic element. This type of pressure transducer is called a linear variable inductance transducer (LVDT) and requires AC excitation voltage. Fig. 3-9 shows a capacitance-type transducer. As the diaphragm moves, the two plates of a capacitor move closer together with a resulting increase in capacitance. Capacitive pressure transducers also require AC excitation voltage.

### Temperature transducers

Body temperature measurement is an important parameter for health-care workers. Although the health-care provider can place a hand on a patient's head and estimate body temperature, modern health care requires far more accurate measurements. For acute-care clinicians, the core body temperature is one of the most important clinical



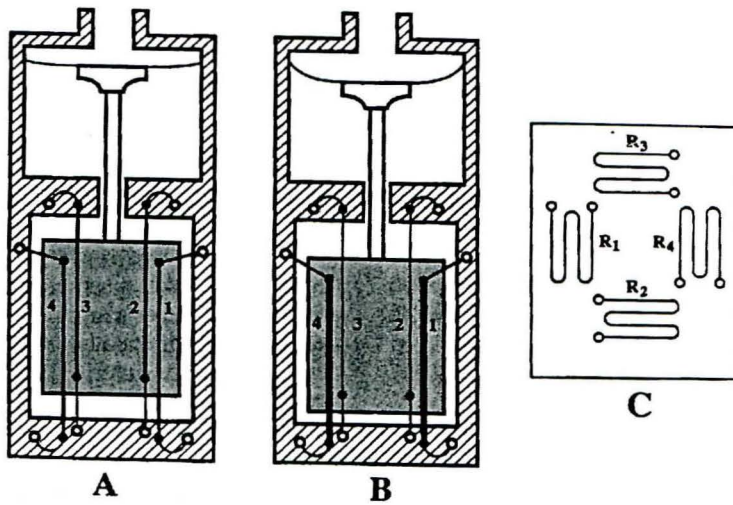


Fig. 3-6. Examples of resistive-type pressure transducers. **A**, Pressure transducer in "zero" position (1, 2, 3, 4 are wires that change dimension when a positive pressure or vacuum is applied). **B**, Pressure transducer with positive pressure applied. Note the downward movement of the diaphragm in the upper section. Also note that "wires" 1 and 4 are "thicker" and wires 2 and 3 are "thinner" than in **A**. All dimensions are grossly exaggerated to illustrate the concepts. **C**, Configuration of the resistor connections used in **A** and **B** with resistors mounted on the diaphragm.

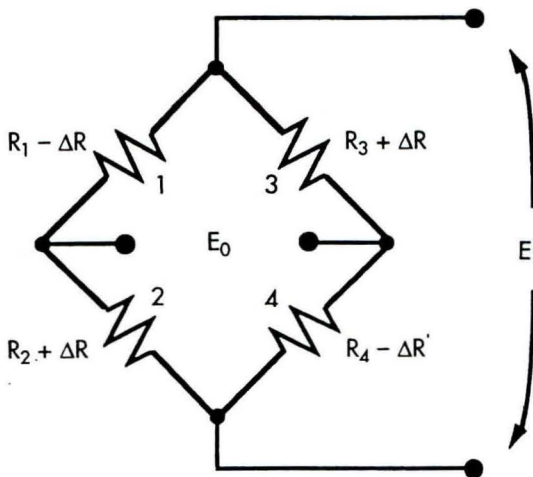


Fig. 3-7. Wheatstone bridge. Connection of resistors shown in Fig. 3.6. Note that resistors 1 and 4 decrease resistance by a small amount ( $\Delta R$ ) while resistors 2 and 3 increase in resistance by a  $\Delta R$ .  $E_0$ , Output voltage;  $E$ , input or excitation voltage.

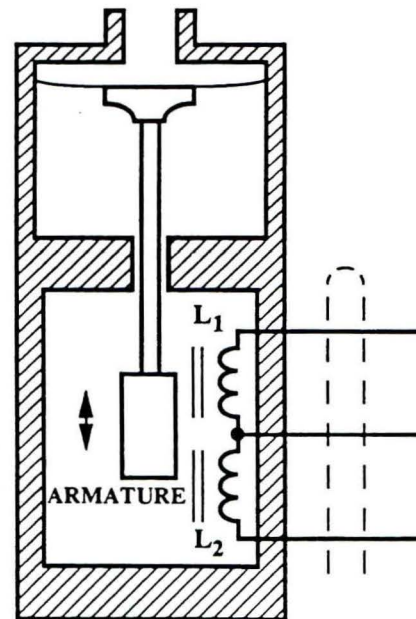


Fig. 3-8. Linear variable inductance transducer (LVDT) pressure transducer.  $L_1$ , Indicator that decreases its value with applied pressure;  $L_2$ , indicator that increases its inductance with applied pressure.

parameters measured. The classic mercury-in-glass thermometer may perform adequately for an occasional noninvasive measurement of body temperature, but modern technology has provided better devices for use in the acute care setting. Factors to consider are size, speed of transducer response, and sensor durability. For example, the temperature transducer on a pulmonary artery catheter must be small enough to fit inside the catheter, and it must have high sensitivity and rapid response so that it can measure small temperature changes in

the patient at room temperature or when iced saline is injected for thermodilution cardiac output measurements. Thermocouples and thermistor sensors are convenient electronic substitutes for the glass thermometer. They can be of small size, they have a fast response time, and they are durable and inexpensive.<sup>1,8-11</sup>

**Thermistors.** Thermistors are small beads (about 0.2 mm in diameter) that are fabricated by forming a powdered semiconductor material (usually a metal oxide) around two lead wires.<sup>1</sup> By heating the semiconductor material to high temperature (called sintering), the material forms a small pellet. The resistance change versus the temperature of the resulting thermistor is very large (much larger than for a piece of copper or tungsten wire). Thermistors have unique and highly stable performance characteristics. Unfortunately, the resistance versus temperature characteristic of the thermistor is nonlinear (Fig. 3-10). Small-diameter thermistors have response times of less than 0.1 second and have a temperature range of 100° C. They can be adjusted at the factory to be interchangeable to within  $\pm 0.1^\circ$  C. Thermistors have very high sensitivity, much greater than thermocouples, and they also have better resolution.<sup>1,12</sup> As noted above, their primary disadvantage is that they have nonlinear resistance versus temperature characteristics.

**Thermocouples.** If two dissimilar metals such as copper and constantan (an alloy of 55% copper and 45% nickel) are wound in contact with each other, a small voltage can be measured across the contact junction.<sup>1,12</sup> This small voltage varies with

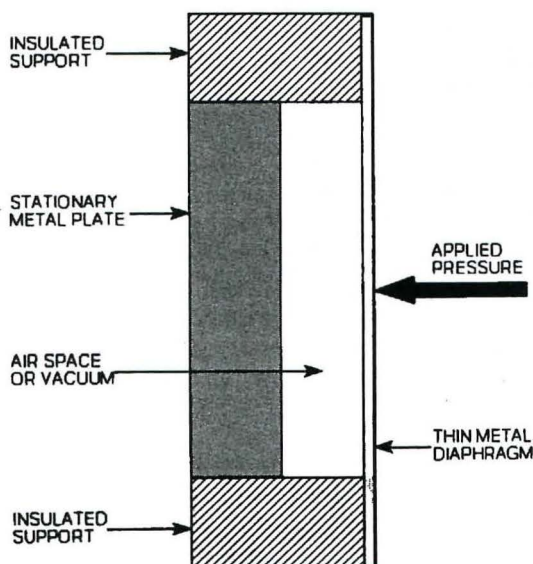
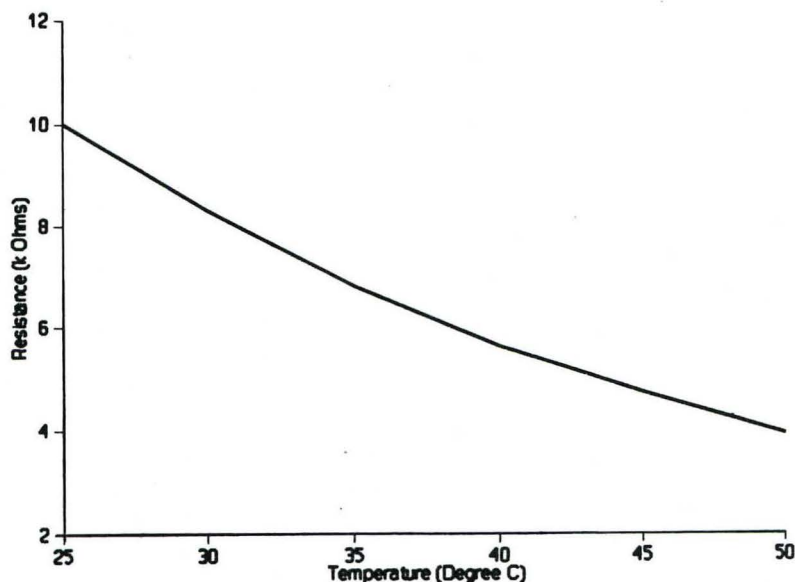


Fig. 3-9. Capacitive pressure transducer.

Fig. 3-10. Thermistor nonlinear characteristics.





temperature and can be used to measure body temperature. For human temperature measurements, the combination of copper and constantan is ideal. This sort of thermocouple is called a T type and has a sensitivity of about  $43 \mu\text{V per } ^\circ\text{C}$ . They have excellent linearity over the temperature range of  $25^\circ\text{C}$  to  $50^\circ\text{C}$ ; they are also inexpensive and have good stability.

**Radiation thermometry.** The theoretical basis of radiation thermometry is that there is a known relationship between the surface temperature of an object (say the tympanic membrane in the ear) and its radiant power.<sup>1,13</sup> Thus it is possible to measure the temperature of the tympanic membrane without ever touching it. Every object that has a temperature above zero degrees Kelvin radiates electromagnetic power. The radiation emitted from an object is a complex matter described in detail by Webster.<sup>1</sup> Energy radiated by human skin at normal body temperatures is in the infrared range (about  $9.66 \mu\text{m}$ ). Unfortunately, the signals transmitted by human skin are not consistent and the amount of energy radiated by the skin is very small. However, successful use of sensor technology and microprocessors has made the use of radiation thermometry practical in the clinical situation. Hand-held instruments that measure the magnitude of infrared radiation from the tympanic membrane are commonly used in the clinical setting. The tympanic membrane and the hypothalamus, the body's main thermostat, are supplied by the same vasculature. Tympanic membrane temperature can therefore provide a good approximation of core temperature. The primary advantage of this technique is that it can measure temperature within less than 1 second with an accuracy of about  $0.1^\circ\text{C}$ .<sup>1</sup> Other thermometer devices, such as the mercury thermometer, must equilibrate to body temperature; this may take up to a minute or longer.

**Spectrophotometry/colorimetry.** The colorimetric method is based on how molecules absorb light. A variety of instruments used in the acute care set-

ting depend on choosing the appropriate wavelengths of light. Examples include both mixed venous oximeters and arterial pulse oximeters.<sup>14</sup> When light passes through the sample or tissue to be measured, typically the Beer-Lambert law applies. This fundamental law has characteristics defined by the equation

$$\ln(I_0/I) = KCL$$

where

$\ln$  = the natural logarithm

$I_0$  = the incident light

$I$  = the measured output light

$K$  = a constant that depends on the properties of the substance

$C$  = the concentration of the substance being measured

$L$  = the thickness of the material being measured

**Bedside oximetry.** Two types of bedside oximetry, absorbance and reflection, are used in the acute-care setting. Both are outgrowths of work done by Earl H. Wood at the Mayo Clinic in 1949.<sup>15</sup> Absorption oximetry is used in the pulse oximeter. Oxygen saturation is determined using the Beer-Lambert law by shining specific wavelengths of light through the finger, ear, or nose and measuring how much light is absorbed by oxygenated and reduced hemoglobin. The reflectance oximeter principle is used with mixed venous oximeters. By measuring the amount of light reflected by hemoglobin at specific wavelengths, the saturation of venous blood in the pulmonary artery can be determined.<sup>15,16</sup>

**Pulse oximeters.** Pulse oximeters use two light-emitting diodes (LEDs) to shine known wavelengths of light through the finger, ear, or nose. On the side opposite the LEDs is a small photodiode detector used to sense transmitted light (Fig. 3-11). These probes are inexpensive and frequently disposable.<sup>17-20</sup> LEDs are used in virtually every electronic device in use today—they are those small green or red "on" indicators on, for example, television sets and computers. The LEDs used for pulse oximeters are specially made to have emis-

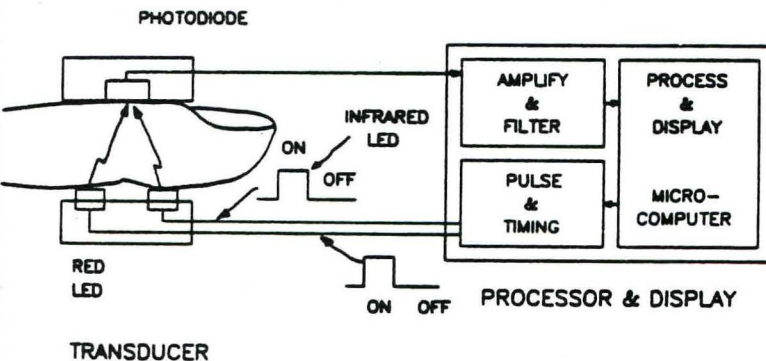
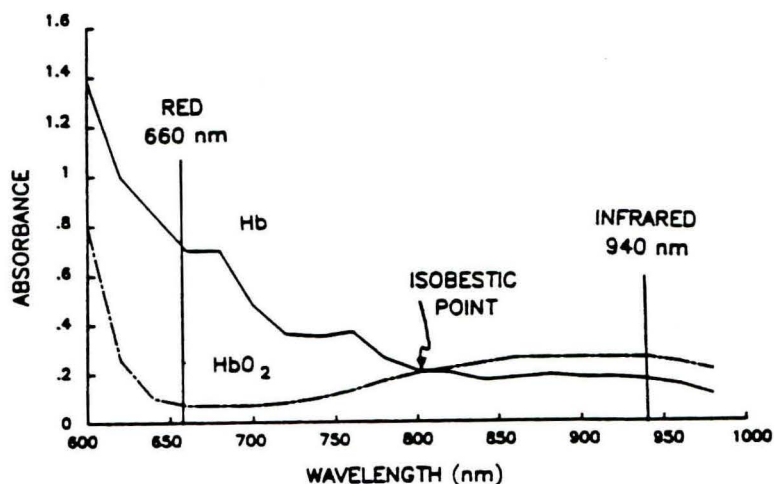


Fig. 3-11. Schematic of a pulse oximeter. LED, Light-emitting diode.

Fig. 3-12. Spectral characteristics of a pulse oximeter. *HG*, Hemoglobin; *HbO<sub>2</sub>*, oxyhemoglobin.



sions of light in the red and infrared spectral range (Fig. 3-12). The Beer-Lambert law is then applied along with special signal processing to derive arterial oxygen saturation. (See Chapter 14 for further discussion.)

**Mixed venous oximeters.** Although measurement of oxygen saturation by reflected light was first described in 1949,<sup>15</sup> it was not until inexpensive fiber-optic materials were made available that it became practical.<sup>16,21</sup> Today, small fiber-optic bundles are housed within a pulmonary artery catheter; with small, inexpensive, reliable light sources and photodetectors, use of reflectance technology is practical. Disposable pulmonary artery catheters with fiber-optic bundles are now widely used to measure mixed venous oxygen saturation in the pulmonary artery.

### Measurement of respiratory gas flow

The primary sensors used for measurement of gas flow are: pneumotachographs, rotameters, ultrasonic flowmeters, and thermal flowmeters.<sup>5</sup> The most commonly used flowmeter is the Fleisch pneumotachometer, invented in 1925 and named after its inventor.<sup>22,23</sup> The pneumotachometer and its more modern variants place a "resistance" in the flow path and measure a pressure drop across that resistance using Ohm's law explained above. Fig. 3-13 is a schematic of a Fleisch pneumotachometer with its attached pressure transducer. Unfortunately, the resistance of the pneumotachometer is *not* linear and is affected by gas composition and upstream flow disturbances.<sup>23,24</sup>

Rotameter flowmeters place a small turbine (windmill) in the flow path and measure the velocity of its rotation. For steady flows and gas compositions (neither of which apply to the breathing patient in acute care) the rotameter can be very

accurate. Ultrasonic flowmeters measure disturbances called vortices in the flow path to measure flow. Unfortunately, like rotameters they are sensitive to gas concentration and irregular flow disturbances. Thermal flowmeters, also called "hot wire" anemometers, measure gas flow by determining how much the flow cools a heated wire (the faster the flow, the more the cooling). In clinical practice, the limitation of these devices is that they are unidirectional and subject to becoming inaccurate because of mucous plugs that may become attached!

### Measurement of respiratory gas concentration

Respiratory gases ( $O_2$ ,  $CO_2$ ) and blood gases ( $O_2$ ,  $CO_2$ , pH) are measured using a variety of sensors.<sup>25-34</sup> If blood gases are to be measured in the laboratory, usually fixed electrodes are used to measure the gas partial pressure.<sup>25-29</sup> However, if the gases are to be measured in the respiratory circuit, other devices such as mass spectrometers are used.<sup>29-34</sup> The details of these sensors and techniques are included in Chapters 13 and 14.

### THE FUTURE OF SIGNAL DETECTORS

The state of the art of technology has advanced dramatically over the past three decades. The ability to use micromachining provided by development in electronic fabrications will likely continue to allow us to make smaller, less expensive, and probably implantable sensors.<sup>5</sup> Biosensors, today's equivalent of the canary in the coal mine, are becoming more common.<sup>35</sup> Therefore, as our students have the opportunity to read what we have written today about sensors, they will certainly think we were not very creative in the use of state-of-the-art technology. We are likely to be viewed much like the pioneers who settled the Western



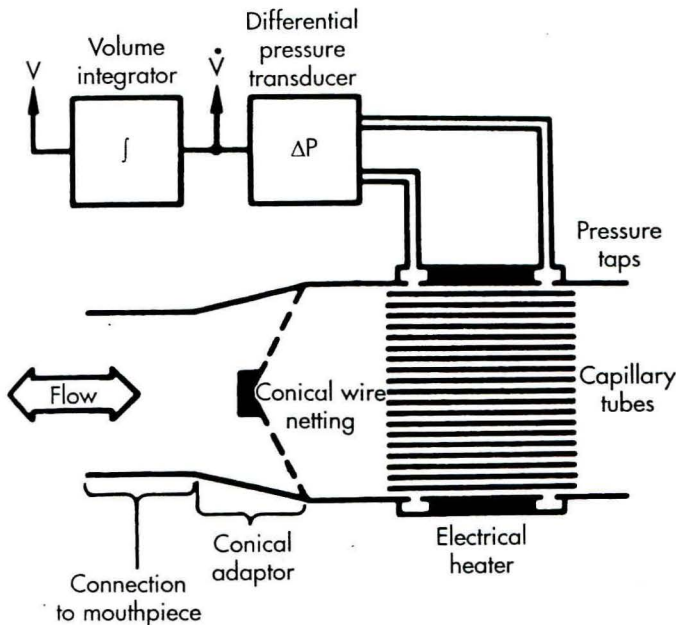


Fig. 3-13. Fleisch pneumotachometer.

United States, as riding in Conestoga wagons on horse trails—a far cry from the automobiles and freeways of today.

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